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The Magnetic Field of Solar Spicules

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Summary. Determining the magnetic field of solar spicules is vital for developing adequate models of these plasma jets, which are thought to play a key role in the thermal, dynamic, and magnetic structure of the chromosphere. Here we report on magnetic spicule properties in a very quiet region of the off-limb solar atmosphere, as inferred from new spectropolarimetric observations in the He I 10830 Å triplet. We have used a novel inversion code for Stokes profiles caused by the joint action of atomic level polarization and the Hanle and Zeeman effects (HAZEL) to interpret the observations. Magnetic fields as strong as 40 G were unambiguously detected in a very localized area of the slit, which may represent a possible lower value of the field strength of organized network spicules.

1 Introduction

The first observational evidence of solar spicules came in the drawings of Father Angelo Secchi in the late nineteenth century. He recorded the shape of these off-limb jet-like structures and listed some of their properties. Spicules can be described as rapidly evolving chromospheric plasma jets, protruding outside the solar limb into the corona. It is thought that they constitute an important ingredient of the mass balance of the solar atmosphere, since they are estimated to carry about 100 times the mass of the solar wind. After the spicular material is shot up (with typical apparent velocities around 25 km s^{-1}) and has reached its maximum height, it returns to the surface along the same path or a different one. However, many spicules do not seem to retract, but rather fade away (see De Pontieu et al. 2007). The average direction of spicules deviates from the vertical, reaching typical heights of 6500 – 9500 km. Observations yield densities about $(3 \cdot 10^{-13} \text{ g/cm}^3)$ and temperatures in the range 5000 – 15000 K that seem to be constant with height (see Beckers 1972 for an early review of spicule properties).

All classical spicule models make use of a magnetic flux tube that expands from the photosphere all the way up into the corona as their main ingredient (e.g., Sterling 2000, De Pontieu et al. 2004). An injection of energy into the flux tube is required to launch the material and to raise it up to heights of several thousand kilometers. Although the various models seem to explain some of the observational aspects of quiet-Sun spicules, they all fail to reproduce one or other observed parameter. One of the key impediments is our poor knowledge of the magnetic properties of spicules. We need more and better observations to constrain the models, and this is what motivates the present investigation. We want to find reliable constraints of some of the physical aspects of spicules, focusing, in particular, on understanding the magnetic field topology and its behaviour along the length of the spicule.

We use new spectropolarimetric measurements of the He I 10830 Å multiplet beyond the limb to infer the magnetic properties of quiet-Sun spicules. The information was retrieved by inverting the observed Stokes profiles (caused by atomic level polarization and the Hanle and Zeeman effects), as was first done by Trujillo Bueno et al. (2005). These authors inferred strengths of 10 G in quiet-Sun spicules at an atmospheric height of 2000 km. They point out, however, that significantly stronger fields could also be present (as indicated by larger Stokes- V signals detected during another observing run). The possibility of magnetic fields significantly larger than 10 G was also tentatively suggested by the He I D₃ measurements of López Ariste & Casini (2005), although these spicules emanated from active plage. More detailed spectropolarimetric observations of spicules in the He I D₃ multiplet were carried out by Ramelli et al. (2006), who found $B \approx 10$ G in quiet Sun and $B \approx 50$ G in more active areas. The presented He I 10830 Å spectropolarimetric observations of quiet-Sun spicules provide an unambiguous demonstration that the magnetic field strength of some spicules can be significantly large.

2 Observations

Observations were carried out with the Tenerife Infrared Polarimeter (TIP, Martínez Pillet et al. 1999) at the German Vacuum Tower Telescope (Tenerife, Spain) on August 17, 2008. The TIP instrument allowed us to measure (almost) simultaneously the full Stokes vector of the 10830 Å spectral region for all the points along the spectrograph slit, with spectral and spatial samplings of 11 mÅ and 0.17'', respectively. Standard data reduction routines were applied to all the data-sets, encompassing dark current and flat-field correction of the images as well as polarization calibration and cross-talk correction of the Stokes profiles.

We placed the slit 2'' off, and parallel to, the visible South limb, crossing a forest of spicules. There, we carried out several time series with the slit at fixed distances to the visible limb. The seeing conditions were not optimal and the off-limb pointing rendered the Adaptive Optics system inoperable.

However, the atmospheric conditions were very stable (no wind), warranting image stability with no coelostat vibrations during the runs. Each data-set of 50-min duration was averaged in time in order to obtain a large S/N ratio. Spectral and spatial pixel binning were performed for the same purpose, maintaining sufficient sampling ($\approx 0.7''$).

3 Analysis

Solar magnetic fields leave their fingerprints on the emergent polarization patterns of spectral lines that form in the solar atmosphere. This occurs through the Hanle and Zeeman effects.

The spectral line polarization produced by the Zeeman effect is a consequence of the wavelength shifts between the π and σ components of the atomic transitions, as the energy levels split due to the presence of a magnetic field. This splitting is normally proportional to the magnetic field strength and the Landé factor of the level. Typically, fields of 100 G or more are needed to be able to observe the signature of the transverse Zeeman effect on the Stokes Q and U profiles of a spectral line, while much weaker resolved fields are enough to produce measurable Stokes- V signals via the longitudinal Zeeman effect. However, when the magnetic field is too weak and/or when there are mixed magnetic polarities within the spatio-temporal resolution element, the circular polarization produced by the longitudinal Zeeman effect tends to be negligible.

Fortunately, even in the absence of magnetic fields, measurable polarization signals in a spectral line occur if there are population imbalances among the magnetic sublevels of the atom. The key mechanism that produces this so-called atomic level polarization in the solar atmosphere is the anisotropic illumination of the atoms. Such “optical pumping” needs no magnetic field to operate and it is very effective in generating atomic level polarization when the depolarizing rates from elastic collisions are low. Structures such as chromospheric spicules are subject to the center-to-limb (CLV) variation of the photospheric illumination, receiving more radiation from the plasma that is directly underneath them than from the sides.

The Hanle effect is the modification of the atomic level polarization due to the presence of a magnetic field inclined with respect to the axis of symmetry of the radiation field. It is sensitive to weaker magnetic fields than those needed to induce a measurable Zeeman polarization signal and it does not tend to cancel out when mixed polarities are present (see Trujillo Bueno 2005). The observational signatures of the Hanle effect in the 90° scattering geometry of our observations are a reduction of the linear polarization amplitude and a rotation of the direction of linear polarization, with respect to the unmagnetized case.

The formation of the He I 10830 Å triplet is sensitive to both the Zeeman and Hanle effects. We have taken advantage of this fact to “measure” the magnetic field in spicules.

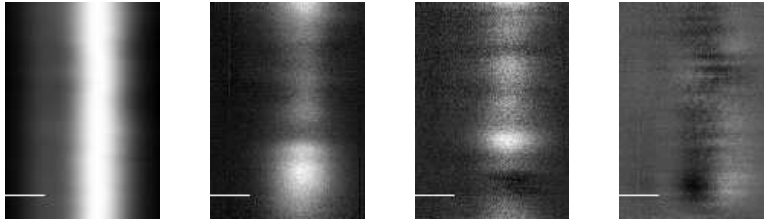


Fig. 1. From left to right, maps of Stokes I , Q , U and V . The x -axis represents wavelength (increasing to the right), the y -axis the position along the slit (which is about $80''$ long).

3.1 Detection of Zeeman-induced Stokes V

The left-most panel of Fig. 1 shows time-averaged intensity as a function of wavelength and position along the slit. The bright and fainter vertical strips correspond to the red and blue components of the He multiplet, respectively. Stokes I provides physical and thermodynamical information: the damping, the Doppler width, the optical depth and the macroscopic velocity of the plasma. Combining it with the information carried by Stokes Q and U (second and third panels, respectively), one can infer the magnetic field orientation. However, in the Hanle saturation regime (which is above about 8 G for this multiplet), linear polarization is barely responsive to the magnetic field strength, hindering its determination.

One of the most striking findings in this particular observation was the clear detection of a Zeeman-induced Stokes- V signature (right-most panel of Fig. 1). The circular polarization signal was, in many cases, large enough that it allowed us to pin down magnetic field strengths beyond the Hanle saturation value. The antisymmetric Stokes V profile must be produced by a net line-of-sight (LOS) component of the magnetic field, B_{LOS} , that would be fully resolved. However, cancellation effects due to the unresolved magnetic structure in our spatio-temporal resolution element (or along the line-of-sight), make the inferred B_{LOS} a lower limit for the field strength. For the profiles in Fig. 2 (indicated by the horizontal lines in Fig. 1), the inferred value is $B_{\text{LOS}} \approx 25$ G, provided by HAZEL.

How do we interpret this signal? In a picture where the spicules are oriented arbitrarily along the line of sight, we would expect the B_{LOS} to cancel, producing no net Zeeman Stokes V . However, these data would seem to imply a preferred direction of the magnetic field. Along the slit there are areas of

strong and weak Stokes- V signals, suggesting that, in the latter cases, the magnetic field is conspiring to minimize (or, at least, reduce) the net LOS component.

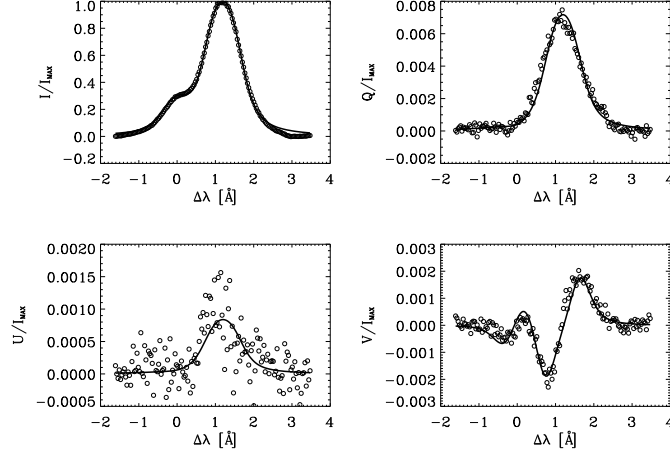


Fig. 2. Best fit produced by HAZEL for a set of Stokes profiles for one position along the slit that has a sizable Stokes- V signal, with $B = 36$ G, $\theta_B = 38.6^\circ$ and $\chi_B = -2.2^\circ$. The reference direction for Q is the tangential to the closest solar limb.

3.2 Inversions

In order to determine the magnetic field strength and other physical quantities from the observations, we inverted the full Stokes vector for every position along the slit using the inversion code HAZEL (see Asensio Ramos et al. 2008) to complete this task. HAZEL accounts for the physical ingredients and mechanisms operating in the generation of polarized light in this kind of observations: optical pumping, atomic level polarization, and the Hanle and Zeeman effects. Radiative transfer is computed in a constant-property slab that is permeated by a deterministic magnetic field. The slab is located at height h above the visible solar surface, and is illuminated by the CLV of the photospheric continuum. The slab's optical thickness, τ , accounts for the integrated number of emitters and absorbers along the line of sight, taking care of the collective effect of having several spicules interposed along the path (although we cannot prescribe how many).

Fig. 2 is an example in which our measurement shows a sizable Stokes- V profile, at the location shown in Fig. 1. The open circles represent the observed profiles while the solid line shows the best fit (in a χ^2 sense) obtained

from a HAZEL inversion. The inferred magnetic field strength is 36 G, with inclination 38.6° from the solar local vertical, and azimuth -2.2° with respect to the LOS. The magnetic field orientation is very well constrained by the observed Stokes Q and U profiles. Except for the 180° and the Van-Vleck ambiguities (see Asensio Ramos et al. 2008 and references therein), a good fit is only possible in a very narrow range of values. However, the field strength is only well determined when the Stokes- V signal is present.

We applied this inversion procedure to all the pixels along the slit and both data-sets, deriving the magnetic field for all the spatial positions at two heights above the visible limb. From these inversion we were able to trace the magnetic field vector and construct a reliable picture of its behavior along the spicules. Variations of the field strength and topology were detected which we will describe in detail in forthcoming publications. Likewise, new observations will be carried out in 2009 to complement this preliminary work.

4 Conclusion

We carried out spectropolarimetric measurements of quiet Sun spicules in the He I 10830 Å triplet, detecting clear Stokes V signals that allow us to infer magnetic field strengths beyond the Hanle saturation regime. Values as high as 40 G were found in localized regions of the slit, which may correspond to organized network spicules or perhaps a macro-spicule.

We determined the magnetic field vector of all the pixels along the slit at two heights from the South limb, detecting spatial variations in the magnetic field strength and orientation. We plan to pursue this investigation further with new observations in the 10830 Å multiplet complemented with other useful data, such as H α or Ca II filtergrams and He D₃ spectropolarimetry.

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